FACTORS INFLUENCING THE STRENGTH AND DUCTILITY OF SLOTTED TENSILE SPECIMENS OF STRUCTURAL STEEL PLATE

BY

PRYOR NEIL RANDALL

B.S., University of Illinois, 1942

AN ABSTRACT OF A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN ENGINEERING
IN THE GRADUATE COLLEGE OF THE
UNIVERSITY OF ILLINOIS, 1948

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Introduction

The high incidence of serious fractures in the hull plating of welded steel merchant ships, in World War II, led to a number of laboratory investigations of the causes of cleavage fracture in structural steel plates. The tests on flat plates which most nearly represented the field conditions found in ships' decks were those conducted at Illinois* and at California.** They consisted of static tension tests of specimens cut from ¾-in. plates to widths varying from 12 in. to 72 in. Each specimen contained a severe internal stress raiser consisting of a transverse slot across the middle one-fourth of the width of the specimen, ending in a jeweler's saw cut. It was found in these investigations that strength decreased with increasing specimen width and approached the yield point of the plate material for the 72-in. specimens.

Subsequently, a number of tests were made of similarly-notched tensile specimens which were two or three inches wide, in an attempt to develop a small specimen test which would predict the results found in the wide-plate investigations. Such a specimen is needed as a research tool which will be more economical than the wide-plate specimens, and also as a quality-control test to determine the suitability of steel plate for structural purposes. Unfortunately, the small specimens exhibited strengths approximately equal to the coupon ultimate strength of the material, and their tempera-

*Wilson, W. M., Hechtman, R. A., and Bruckner, W. H., **Final Report on Cleavage Fracture of Ship Plates as Influenced by Size Effect**, National Research Council, Division of Engineering and Industrial Research, Committee on Ship Construction, Report Serial No. SSC-10, June 12, 1947.

Davis, H. E., Troxell, G. E., Parker, E. R., Boodberg, A., and O'Brien, M. P., **Final Report on Causes of Cleavage Fracture in Ship Plate: Flat Plate Tests and Additional Tests on Large Tubes, National Research Council, Division of Engineering and Industrial Research, Committee on Ship Construction, Report Serial No. SSC-8, January, 1947.

ture of transition from high to low energy absorption was, on the average, 30 deg. F. lower than that of the wide-plate specimens of the same steel. It is true that both types of specimens had the same thickness and the same stress raiser, and therefore could not be considered geometrically similar in all respects.

The first purpose of this investigation was to see if the differences in strength and ductility noted above were due to differences in size or to lack of geometric similarity. The principal tests conducted to answer this question were a size-effect series in both a killed steel and a rimmed steel, using four sizes of geometrically similar specimens. The second purpose was to investigate the apparent dependence of the strength of the wide-plate specimens on the yield point of the plate material. A qualitative analysis for the strength of specimens of this type was developed, and tests were conducted on three groups of 12-in. wide specimens which had been prestrained through the yield-point elongation before being notched.

Description Of Tests

1. Specimens

All of the steel used in the size-effect study had been rolled under specifications A. S. T. M. A-7-41. In carrying out this study, the following tests were performed.

A preliminary series of tests was conducted to determine the relative severity of four internal stress raisers, consisting of a transverse slot across the middle half of the width of the specimen, and ending in: (1) a 0.012-in. wide jeweler's saw cut, (2) a 0.038-in. wide hack saw cut, (3) a 0.038-in. diameter drilled hole, and (4) a 0.15-in. diameter drilled hole. These specimens were 2¼ in. wide by ¾ in. thick and were cut from ¾ in. by 2½ in. bars of killed steel, normalized.

The principal group of tests was a size-effect series, using four sizes of geometrically similar specimens, whose dimen-

sions varied in the proportions 1, 2, 3, and 5. The smallest specimens were ¼ in. thick by 1½ in. wide and the largest ones were 1¼ in. thick by 7½ in. wide. They all contained an internal stress raiser composed of a transverse slot across the middle half of the width of the specimen, ending in a small drilled hole, the diameter of which was proportional to the other dimensions. In the ¼-in. specimens, the slot ended in a jeweler's saw cut, 0.012 in. wide, the bottom of which had been lapped round. All sizes of specimens were of full plate thickness. The ¼-in. specimens were cut from ¼-in. by 2½-in. bars. This difference, plus that noted above in the formation of the stress raiser, was taken into account in weighing the test results. The size-effect series was carried out in both a killed steel and a rimmed steel. The specimens were normalized in bundles of equal cross section to produce equal cooling rates in all sizes.

Control tests were conducted on the material of the size-effect series, using Kahn tear-test specimens of reduced size, which were machined from the core material of the plates in question. These were in addition to the standard tensile tests of unnotched rectangular bars.

In studying the dependence of the strength of wide-plate specimens on the yield point of the material, the following tests were conducted. All the specimens were ¾ in. thick by 12 in. wide, and the stress raiser was a transverse slot across the middle one-fourth of the specimen, ending in a jeweler's saw cut. The specimens were identical in geometry to the 12-in. specimens tested in the wide-plate investigation at the University of Illinois. A group of four tests was conducted in killed steel, D, and a similar group in rimmed steel, E, of the wide-plate investigation. The mechanical properties of both steels satisfied the requirements of specifications A. S. T. M. A-7-41. These specimens were strained about 3 per cent before being notched and tested. This removed the yield point and gave a smooth, steadily increasing stress-strain curve. In a third group of five tests on the rimmed steel, the

specimens were aged after straining and before being notched and tested. The aging gave a new yield point about 88 per cent higher than the original yield point.

2. Principal Data Taken

Each group of tests included from four to eight specimens of identical geometry, which were tested at different temperatures to obtain the temperature of transition from high to low energy absorption. The data taken during each test were the temperature of the specimen and a number of readings of load vs. elongation. The most significant values obtained from each group were the ultimate strength and the absorbed energy for each specimen and the transition temperature range for the group. The total energy was measured in two parts, that absorbed before maximum load and that absorbed after maximum load. The broken specimens were measured to obtain the final elongation and the reduction of area, and the surfaces of the fracture were examined to determine the percentages of shear and cleavage fracture.

All specimens, except the 12-in. plates, were polished to reveal the Lüders' bands, which indicate the extent of plastic deformation. These gave sufficient information to permit the measurement of the volume of metal which had undergone plastic deformation.

3. Testing Techniques

Temperature control was achieved throughout each test by immersing the test section of the specimen in a liquid contained in a tank which surrounded the specimen. For tests below room temperature, the liquid was Stoddard solvent, cooled by dry ice. For tests above room temperature, water heated by steam was used.

Temperatures were measured by means of a copper-constantan thermocouple soldered to the specimen outboard from the stress raiser. A rough check was obtained by means of a thermometer held in the liquid in the tank. The tem-

perature of test recorded for each specimen was the average measured by the thermocouple just prior to and during the attainment of maximum load.

The transition temperature range given for a group of specimens was that of a transition in absorbed energy from a rather constant upper value for specimens failing by shear to a rather constant lower value for specimens failing by cleavage. Very few intermediate energy values were found.

In all except the prestrained specimens, the net area was equal to one-half the gross area. Therefore, plastic deformation occurred only in the vicinity of the stress raiser. Gage lengths were made long enough to span the entire plastically deformed region. Hence, the values of absorbed energy reported herein may be considered the total energy expended in plastic deformation of the specimen.

Summary Of Strength Features Of The Tests

The first step in this study was the development of an analysis for the strength of internally-notched tensile specimens of structural steel plate. This formed the basis for the interpretation of the strength features of the tests made in this investigation, as well as in certain previous tests. It was first developed in a qualitative way from knowledge of the stress-strain curve of the material and from photographic evidence of the extent of plastic deformation in both narrow and wide-plate specimens. Subsequently, some data from the wide-plate investigation at Illinois were used to substantiate the analysis and to put it on a somewhat more quantitative basis.

The strength of a wide-plate specimen was analyzed by dividing it into longitudinal strips and developing a load-elongation curve for each strip. The basic assumption was made that the behavior of, let us say, the strip adjacent to the end of the stress raiser was unaffected by a change in the

number of strips adjoining it. Parker* has stated that the strain concentration at the base of the notch was substantially the same for all widths of specimens tested in the wide-plate investigation at California.

The effect of an increase in the width of the specimen was studied by considering the effect of adding a number of longitudinal elements at each edge of the specimen. Similarly, the effect of a change in the severity of the stress raiser on the strength of the specimen was studied by considering its effect on the load-elongation curve of the strip adjacent to the end of the stress raiser, and also its effect on the elongation to maximum load for specimens failing by shear, and for specimens failing by cleavage.

It was found that predictions based on the analysis agreed quite well with certain trends shown by the test results of this and previous investigations. They were as follows:

(a) The strength of specimens which fail by shear will decrease as the width of the specimen increases, from values approximately equal to the coupon ultimate strength of the plate material (at the temperature of test) for narrow specimens, to values approximately equal to the yield point of the plate material for wide specimens. The value of the yield point at the temperature of test may be considered to be the lower limit of the strength values, provided the specimens fail by shear fracture.

(b) The strength of specimens which fail by cleavage will also decrease as the width of specimen increases. For narrow specimens, the strength of those which fail by cleavage will not differ markedly from the strength of those which fail by shear. For wide specimens, however, the strength of those which fail by cleavage may be somewhat below the yield point of the plate material at the temperature of test.

(c) The strength of wide specimens is strongly depen-

*Parker, E. R. "The Effect of Section Size on the Fracture Strength of Mild Steel" Fracturing of Metals, American Society for Metals, Cleveland, Ohio, 1948, pp. 82-89.

dent upon the elongation to fracture and, hence, upon the severity of the stress raiser. It is not safe to assume that the yield point serves as the lower limit of the strength values of wide specimens which fail by cleavage, particularly because the maximum severity which a stress raiser in an actual structure may have is not known.

(d) The tests made on 12-in. wide specimens, which had been prestrained to remove the yield-point phenomena, indicated that prestraining had improved the strength of the specimens which failed by shear about 8 per cent for killed steel, D, and about 3 per cent for rimmed steel, E. The strength of the specimens which failed by cleavage was improved about 24 per cent for both steels. Prestraining of the rimmed steel, followed by aging, improved the strength of the specimens which failed by shear about 10 per cent, and those which failed by cleavage about 36 per cent. These test results were in agreement with predictions based on the strength analysis.

(e) In the size-effect study made in this investigation, the strength increased from 2000 to 3000 lb. per sq. in. with each decrease in size from 1¼ in. thick to ¾ in. to ½ in. to ¼ in. This was partially, but not completely, explained by the differences in the coupon ultimate strength of the materials of different thickness. It was also found that the relative elongation to maximum load was greater for the smaller sizes of specimens. On the basis of the strength analysis, it was reasoned that this produced a greater degree of strain hardening in the smaller specimens, and resulted in greater strength. In other words, part of the size effect in strength was felt to be due to a size effect in the ductility of the specimens. It was therefore concluded that the observed differences in the strength of the specimens of different sizes were partly explained by differences in the material, but some of the differences may have been due to differences in size.

Summary Of Ductility Features Of The Tests

The ductility of each specimen was measured in terms of the energy it absorbed, both before and after maximum load. It was felt that absorbed energy was a measure of the total amount of plastic deformation, regardless of where it had occurred. The correlation obtained between absorbed energy and other measures of ductility was as follows. The ratio between total absorbed energy (per sq. in. of net section) and energy factor (ultimate stress times total elongation) varied from the average of 0.82 by not more than 20 per cent, for all the specimens tested in this investigation. Total elongation may be used as a measure of absorbed energy provided that the strength of all the specimens is substantially the same, and provided that the shape of all the load-elongation curves is the same. Reduction of area may be used as a measure of relative values of absorbed energy, but only with reference to specimens which are exactly alike.

The property of ductility was considered to be inseparable from the characteristics of the fracture which finally occurred. The two types of fracture were called "shear" and "cleavage", since these terms have a definite meaning with regard to the planes of separation in the ferrite grains. It was found in this investigation that a close correlation existed between fracture type and the energy absorbed after maximum load, which was actually the energy required to propagate the crack, once it had reached serious proportions. The energy required to propagate cleavage fractures was practically nil, while for shear fractures it was relatively large. The latter quantity was absorbed in producing a high degree of plastic deformation in the vicinity of the fracture. This was shown by the fact that the energy absorbed per cu. in. of deformed volume was much greater for shear fractures than for cleavage fractures.

Cleavage fractures occurred on planes normal to the axis of the specimen and were characterized by their bright, crystalline appearance. Shear fractures were of two types.

One occurred on planes normal to the axis of the specimen, but was distinguishable from a cleavage fracture by its dull, fibrous appearance. In specimens which failed with a mixed fracture, the boundary between the two types was always quite sharp. The other type of shear fracture occurred on planes inclined at approximately 45 degrees to the axis of the specimen.

A study of the fracture types in all of the specimens led to the observation that a cleavage fracture was always preceded by at least a small, thumbnail-shaped region of shear fracture (largely on a normal plane) adjacent to the end of the stress raiser. It was observed that about 91 per cent of the cleavage fractures had their origin at the edge of a shear fracture on a normal plane. Furthermore, it was noted that once a single shear fracture on an inclined plane was established across the entire thickness of the plate, in 80 per cent of the cases it continued in that form to the edge of the specimen. Apparently the establishment of the inclined plane of fracture reduced the constraint by relieving the tensile stress normal to the plane of the plate at its mid-thickness.

From the observation of fractures and from certain test data, it was concluded that specimens having a notch geometry which permitted the initial shear cracks to be on inclined planes, and of some length, had lower transition temperatures and higher energy absorption below the transition. This was in comparison with specimens whose notch geometry provided such constraint that the initial shear fracture occurred on a plane normal to the axis of the specimen. Also, it seems probable that the severity of an internal stress raiser, as measured by its tendency to produce cleavage fractures, was dependent upon the amount of shear fracture on a normal plane which it produced. These conclusions were used to explain some test data which indicated that a round-bottomed stress raiser was more severe than a square-bottomed stress raiser of the same width.

One of the outstanding features of internally-notched

tensile specimens which have severe stress raisers is the sharpness of the transition from high to low values of absorbed energy. The absence of intermediate energy values for specimens tested in the transition range depends upon two factors. First, the stress raiser must be of such severity that the energy required to propagate a shear fracture is at least equal to the energy absorbed before the initiation of the fracture. Second, the geometry of the specimen must be such that mixed fractures in the range from 5 per cent to 50 per cent shear do not occur. In other words, the change in fracture type must be a complete change, rather than a gradual one, and the drop in the energy of propagation which accompanies the change in fracture type must cause a significant drop in the total absorbed energy.

In the size-effect series in killed steel, the transition temperature for the four sizes increased quite regularly from about −72 deg. F. for the ¼-in. specimens to about −1 deg. F. for the 1¼-in. specimens. For the series in rimmed steel, the same trend existed for the three larger sizes, although the transition temperature of the ½-in. specimens was about −4 deg. F., which seemed abnormally low, compared to +46 deg. F. for the ¾-in. specimens and +62 deg. F. for the 1¼-in. specimens. The transition temperature for the ¼-in. specimens was about +19 deg. F., which seemed abnormally high. The latter were found to have a very coarse microstructure, and this was felt to be a partial explanation for their anomalous behavior.

Although routine tensile tests had been made to check the identity of the materials used for the size-effect series, the results described above made it seem necessary to apply a more severe control test; this was done, using a modified form of the Kahn tear-test specimen. For the killed steel, the trend in transition temperatures for the tear tests was parallel to that for the ¾-in. and 1¼-in. size-effect specimens, but not for the two smaller sizes. For the rimmed steel, the trend in transition temperatures for the tear tests (using ⅜-in. thick

specimens) was not parallel to that shown by the three largest sizes of the size-effect series, but (using three-sixteenth inch thick specimens) the trend was parallel to that shown by the ¼-in. and ½-in. specimens of the size-effect series. It must be concluded that there was some size-effect, as measured by transition temperature, for the two smaller sizes of killed-steel specimens and for the three largest sizes of rimmed-steel specimens. The test results for the ¼-in. specimens in the two steels were conflicting. This may have resulted from certain experimental difficulties. This conflict makes it impossible to draw a general conclusion with regard to size effect in the transition temperatures for very small specimens.

Measurements of absorbed energy for the specimens of the different sizes revealed that this quantity varied much more nearly as the square than as the cube of similar dimensions. Similar findings have been reported in previous investigations. No explanation for this behavior, based on differences in the materials, could be found. It was therefore concluded that there was also some size effect with regard to the energy absorbed by geometrically similar specimens.

A study of the previous data indicated that the transition temperature of the wide-plate specimens was about 30 deg. F. above that of the small specimens, similarly notched. An attempt was made to relate this difference to the difference in stresses produced by the heterogeneous plastic deformation which had been found to occur in wide-plate specimens up to the instant of failure. The tests which were conducted on 12-in. wide plates in which the yield-point phenomena had been eliminated by prestraining indicated that no change in transition temperature had been produced by this treatment. The transition temperature for the group of specimens which were fully aged after prestraining was about 40 deg. F. above that of the specimens which were not aged. While this did not prove that there was no aging in the other two groups of prestrained specimens, it did indicate that much less than complete aging had occurred. It was concluded that the

stresses accompanying the heterogeneous deformation in the wide-plate specimens were not the primary cause of their higher transition temperature.

VITA

Pryor Neil Randall was born in Chrisman, Illinois, October 22, 1920. Upon being graduated from high school at Freeport, Illinois, in June, 1938, he entered the University of Illinois and received the degree of Bachelor of Science in Civil Engineering in June, 1942.

He immediately entered the Army as a Second Lieutenant, AUS, in the Corps of Engineers. He commanded Company F, and later the 2nd Battalion, of the 351st Engineer General Service Regiment, from August, 1942, to October, 1945, his last promotion being to Major, in January, 1945. During this period his unit spent 25 months in Europe, engaged in construction activities in the Zone of Communications.

In November, 1945, upon beginning his terminal leave, he entered the Graduate School of the University of Illinois and was granted the Standard Oil Fellowship for that year. Since that time he has continued his graduate work under that fellowship.